it possible to vary, as may be expedient, not merely the amount of work done per diem, but the distribution of the work in time. In the realisation of this purpose I anticipate great advantage from the use of the work machine, which I have been able to construct for the purpose of my inquiry by the liberality of the British Association.

In conclusion, I would draw attention to the results relating to the influence of work on the discharge of phosphates and sulphates by the urine.

As regards phosphates, it has been shown that no increase occurs unless the exertion is very severe. As regards sulphates, it manifests itself distinctly in many cases, the output of sulphates being in general terms proportional to that of nitrogenous material.

It is a matter of regret that the total sulphur of the food was not estimated. It is known that the percentage of sulphates contained in the food was insignificant as compared with that excreted in the urine, and consequently almost all of the discharge must have been a product of oxidation.

I beg, in conclusion, to state that the expenses of the present research, which have been extremely heavy, have been defrayed by a grant of the British Medical Association. I desire to express to the Association my most grateful thanks.

## "The Influence of Stress and Strain on the Physical Properties of Matter. Part II. Electrical Conductivity (*continued*). The Alteration of the Electrical Conductivity of Cobalt, Magnesium, Steel, and Platinum-iridium by Longitudinal Traction." By HERBERT TOMLINSON, B.A. Communicated by Professor W. GRYLLS ADAMS, M.A., F.R.S. Received October 7, 1884. Read November 20.

### *The Alteration of the Electrical Resistance of Cobalt produced by Longitudinal Traction.*

In a previous communication to the Royal Society,* I pointed out that whilst with iron the electrical resistance is temporarily increased by temporary longitudinal traction, that of nickel is decreased, provided the stress be not carried beyond a certain limit, and this, too, in spite of the change of dimensions, namely, increase of length and diminution of diameter, which follow from the stress. I further showed† that there is a marked resemblance between the table of "rotational coefficients" drawn up by Professor Hall and that laid down by myself from the results of experiments on the effect of

* "Phil. Trans.," vol. 174, p. 58.

† *Loc. cit.*, p. 168.

mechanical stress on the specific electrical resistance of metals. A comparison of the two tables shows, that with the exception of platinum the metals stand in nearly the same order in both, and that iron and nickel are very conspicuous, the former at the top and the latter at the bottom of both lists.

Mr. Shelford Bidwell has also brought forward* very strong evidence in favour of his assertion, that the "Hall effect" can be explained by the joint action of mechanical strain and certain "Peltier effects," and has shown that those metals in which the "Hall effect" is positive are rendered by temporary traction thermo-electrically negative to pieces of the same metal unstretched. It seemed, then, a matter of considerable interest to ascertain whether cobalt would act like iron or nickel as far as the effect of stress on the electrical resistance is concerned, and I endeavoured—for some time in vain—to obtain either wires or strips of cobalt suitable for the purpose in view. At length, through the courtesy of Mr. Wiggin, jun., Birmingham, I found myself in possession of two strips† of cobalt, upon which I was able to make the necessary experiments.

### *Preliminary Determination of the Value of "Young's Modulus," Density, &c.*

The length of each strip was 58·4 cm., and the thickness and width of one of them, when gauged at ten places at equal distances apart, were as follows :—

| Number of observation. | Thickness in centimetres. | Width in centimetres. | Section in square centimetres. |
|---|---|---|---|
| 1 | 0·0864 | 0·7091 | 0·06127 |
| 2 | 0·0870 | 0·7076 | 0·06156 |
| 3 | 0·0851 | 0·7131 | 0·06069 |
| 4 | 0·0858 | 0·7104 | 0·06095 |
| 5 | 0·0857 | 0·7282 | 0·06241 |
| 6 | 0·0848 | 0·7250 | 0·06148 |
| 7 | 0·0850 | 0·7326 | 0·06227 |
| 8 | 0·0849 | 0·7557 | 0·06416 |
| 9 | 0·0846 | 0·7556 | 0·06392 |
| 10 | 0·0854 | 0·7474 | 0·06383 |
| Mean .......... | 0·08547 | 0·72847 | 0·06226 |

The strip was therefore fairly uniform in section throughout, the mean value of the section as determined by the gauge being 0·06226 square centimetre.

* "Phil. Mag.," April 1884, p. 249.

† Mr. Wiggin informed me that he found it impossible to draw *wires* of cobalt, as the metal was so hard that it destroyed the tools with which it was brought into contact. Messrs. Johnson and Matthey were also good enough to attempt to draw for me wires of cobalt, but they too failed through a like cause.

The density of the metal was determined by means of a specific gravity flask, some pieces having been previously broken off for the purpose, and was found to be 8·231 at a temperature of 16° C. The same pieces were well annealed, and the density at 16° C. was then found to be 8·259. The mean section as determined from the mass of the strip 29·65 grams, the length, and the density, was for the unannealed metal 0·06168 square centimetre, and this value, agreeing as it did fairly with that got by gauging, was assumed to be correct.

The modulus of longitudinal elasticity was determined by holding the strip in the centre and rubbing it along its length with a resined glove. The note obtained was very high in pitch, but the results of the measurements of the number of vibrations obtained by the use of the syren agreed very well with each other.*

*Experiment I.*

The lower double octave obtained by rubbing the strip longitudinally was taken on a monochord; the syren was then raised to the pitch of the monochord, and the number of vibrations counted for two minutes at a time.

| Number of trial. | Number of vibrations recorded by the syren in two minutes. |
|---|---|
| 1 | $6286 \times 20$ |
| 2 | 6273 . . . |
| 3 | 6273 . . . |
| Mean .......... | $6277 \times 20$ |

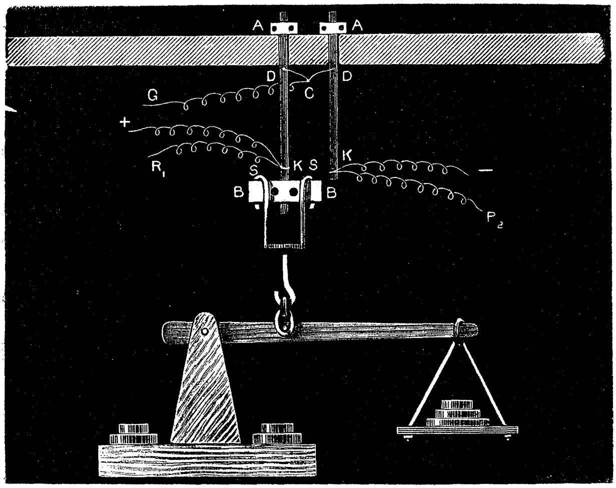
In this experiment the monochord was retuned twice, and it will be observed that the mean value does not differ from any of those forming it by so much as 0·15 per cent. From these last observations the value of "Young's modulus" for the unannealed cobalt was ascertained to be $2005 \times 10^6$ grams per square centimetre. The same strip was then well annealed, and three results, equally as concordant as the last, were obtained when the strip was thrown into longitudinal vibrations. The value of "Young's modulus" of the metal in the annealed condition was $1817 \times 10^6$ grams per square centimetre.

*Arrangement of the Cobalt Strips for Observation on the Alteration of Resistance produced by Longitudinal Traction.*

The two strips (see fig. 1) in the first instance in the unannealed con-

* I have again to thank Mr. Furse, of King's College, for his assistance here.

FIG 1.




dition, passing through two apertures in a table, were secured at their upper extremities to two clamps, A, and the lower extremity of the one to be stretched was fastened to the clamp B, over which passed the double hook S, connected with a stout lever of hard wood. A scale-pan weighing 2 kilos. was suspended at the end of the lever, and by loading and unloading this very carefully the strip was subjected to any required alteration of stress. Short pieces of insulated copper wire were soldered to each strip at D, and the junction, C, of these pieces was united with one terminal of the galvanometer. Two other pairs of similar wires were soldered at K, and one of each pair was connected as usual with resistance coils, and the other with one pole of a single Leclanché cell. The two sets of resistance coils, which in this case were about 10 ohms each, were united by a platinum-iridium wire traversed by a sliding-piece connected with the other terminal of the galvanometer. The mode of experimenting was precisely the same, and the same precautions were taken as in the earlier experiments.*

When the strip had been sufficiently tested in the unannealed condition it was well annealed, and in this new condition again experimented on; but whereas before the stress used was not sufficient to cause any permanent elongation, the strip was now permanently lengthened and the permanent alteration of resistance thus caused was measured as well as the temporary alteration. The following experiment was made on the annealed metal when stressed for the first time after the annealing.

* *Loc. cit.*, p. 45 and p. 54.

*Experiment II.*

| Load =W. | Position of sliding-piece. | Alteration of resistance in terms of divisions of the platino-iridium wire. — signifies decrease of resistance on loading. | Temporary alteration of resistance =T. | Total permanent alteration of resistance =P. | $\frac{T}{W}$. | $\frac{P}{W}$. |
|---|---|---|---|---|---|---|
| 0 | 103·0 | | | | | |
| 2 | 99·0 | − 4·0 | − 4·0 | 0 | −2·00 | |
| 4 | 95·0 | − 8·0 | − 8·0 | 0 | −2·00 | |
| 6 | 93·0 | −10·0 | −12·0 | + 2·0 | −2·00 | +0·33 |
| 8 | 93·0 | −10·0 | | | | |
| 10 | 93·0 | −10·0 | | | | |
| 12 | 98·5 | − 4·5 | −21·5 | + 17·0 | −1·90 | +1·42 |
| 0 | 120·0 | | | | | |
| 2 | 118·0 | − 2·0 | − 2·0 | + 17·0 | −1·00 | |
| 4 | 115·5 | − 4·5 | − 4·5 | + 17·0 | −1·13 | |
| 6 | 113·5 | − 6·5 | | | | |
| 8 | 112·5 | − 7·5 | | | | |
| 10 | 111·5 | − 8·5 | | | | |
| 12 | 112·0 | − 8·0 | | | | |
| 14 | 116·0 | − 4·0 | −20·0 | + 33·0 | −1·43 | +2·36 |
| 0 | 136·0 | | | | | |
| 4 | 133·0 | − 3·0 | − 3·0 | + 33·0 | −0·75 | |
| 8 | 130·0 | − 6·0 | − 6·0 | + 33·0 | −0·75 | |
| 12 | 128·5 | − 8·5 | | | | |
| 16 | 136·0 | 0 | −23·0 | + 56·0 | −1·44 | +3·50 |
| 0 | 159·0 | | | | | |
| 4 | 156·0 | − 3·0 | − 3·0 | + 56·0 | −0·75 | |
| 8 | 153·0 | − 6·0 | − 6·0 | + 56·0 | −0·75 | |
| 12 | 152·0 | − 7·0 | | | | |
| 16 | 154·0 | − 5·0 | | | | |
| 18 | 160·0 | + 1·0 | −23·5 | + 80·5 | −1·32 | +4·47 |
| 0 | 183·5 | | | | | |
| 4 | 181·5 | − 2·0 | − 2·0 | + 80·5 | −0·50 | |
| 8 | 178·5 | − 5·0 | − 5·0 | + 80·5 | −0·63 | |
| 12 | 178·0 | − 5·5 | | | | |
| 16 | 179·5 | − 4·0 | | | | |
| 20 | 190·0 | + 6·5 | −25·5 | +112·5 | −1·28 | +5·63 |
| 0 | 215·5 | | | | | |
| 4 | 213·5 | − 2·0 | − 2·0 | +112·5 | −0·50 | |
| 8 | 210·5 | − 5·0 | − 5·0 | +112·5 | −0·63 | |
| 12 | 209·5 | − 6·0 | | | | |
| 16 | 210·5 | − 5·0 | | | | |
| 20 | 215·0 | − 0·5 | | | | |
| 22 | 223·0 | + 7·5 | −28·0 | +148·0 | −1·27 | +6·73 |
| 0 | 251·0 | | | | | |
| *0 | 66·0 | | | | | |
| 4 | 68·5 | − 2·5 | − 2·5 | +148·0 | −0·63 | |
| 8 | 71·0 | − 5·0 | − 5·0 | +148·0 | −0·63 | |
| 12 | 72·0 | − 6·0 | | | | |
| 16 | 71·5 | − 5·5 | | | | |
| 20 | 69·0 | − 3·0 | | | | |
| 22 | 65·5 | + 0·5 | −24·5 | +173·0 | −1·11 | +7·86 |
| 0 | 41·0 | | | | | |

* Resistance coils readjusted.

In this experiment the numbers given for the load represent the number of kilograms on the end of the lever,* and, when multiplied by 4908, will represent the actual stress on the strip. After a rest of two days with all the stress off, except that produced by the weight of the lever itself,† the resistance had decreased, so that the sliding-piece had to be shifted from 41 divisions to the right of the zero-point to 45 to the left, or through 86 divisions; so that the total permanent increase of resistance was now represented by 87 divisions instead of 173 divisions. The strip was now tested again with the following results:—

*Experiment III.*

| Load. = W. | Position of sliding-piece. | Alteration of resistance in terms of the divisions of the platino-iridium wire. − signifies decrease of resistance on loading. | Temporary alteration of resistance = T. | Total permanent alteration of resistance = P. | $\frac{T}{W}$. |
|---|---|---|---|---|---|
| 0 | 45 left | .. | .. | +87 | |
| 4 | 48 „ | − 3·0 | − 3·0 | +87 | −0·75 |
| 8 | 51 „ | − 6·0 | − 6·0 | +87 | −0·75 |
| 12 | 51 „ | − 6·0 | | | |
| 16 | 50 „ | − 5·0 | | | |
| 20 | 48 „ | − 3·0 | −22·0 | +136 | −1·10 |
| 0 | 26 „ | | | | |
| 20 | 34 „ | − 8·0 | −21·0 | +119 | −1·05 |
| 0 | 13 „ | | | | |
| 20 | 21 „ | − 8·0 | −21·0 | +132 | −1·05 |
| 0 | 0 „ | | | | |
| 20 | 10 „ | −10·0 | −20·0 | +142 | −1·00 |
| 0 | 10 right | | | | |
| 20 | 2 left | −12·0 | −20·0 | +150 | −1·00 |
| 0 | 18 right | | | | |
| 20 | 8 „ | −10·0 | −19·0 | +159 | −0·95 |
| 0 | 27 „ | | | | |
| 20 | 16 „ | −11·0 | −19·0 | +167 | −0·95 |
| 0 | 35 „ | | | | |
| 20 | .. | .. | .. | +175 | |
| 0 | 43 „ | | | | |

* Including the weight of the scale-pan itself.

† This was nearly equal to a load of 1 kilo. on the end of the lever.

20 kilos. were now put on the lever and taken off again six times in succession.

| Load =W. | Position of sliding-piece. | Alteration of resistance in terms of the divisions of the platino-iridium wire. – signifies decrease of resistance on loading. | Temporary alteration of resistance =T. | Permanent alteration of resistance =P. | $\frac{T}{W}$. |
|---|---|---|---|---|---|
| 0 | 77·0 right | .. | .. | +209·0 | |
| 16 | 64·0 ,, | –13·0 | –14·0 | +210·0 | –0·875 |
| 0 | 78·0 ,, | | | | |
| 12 | 68·0 ,, | –10·0 | –11·0 | +211·0 | –0·917 |
| 0 | 79·0 ,, | | | | |
| 8 | 72·0 ,, | – 7·0 | – 6·5 | +210·5 | –0·813 |
| 0 | 78·5 ,, | | | | |
| 4 | 74·5 ,, | – 4·0 | – 4·5 | +211·0 | –1·125 |
| 0 | 79·0 ,, | | | | |
| 4 | 75·0 ,, | – 4·0 | – 4·0 | +211·0 | –1·000 |
| 0 | 79·0 ,, | | | | |
| 4 | 76·0 ,, | – 3·0 | – 4·0 | +212·0 | –1·000 |
| 0 | 80·0 ,, | | | | |
| 4 | 75·5 ,, | – 4·5 | – 3·5 | +211·0 | –0·875 |
| 0 | 79·0 ,, | | | | |
| 4 | 75·0 ,, | – 4·0 | – 3·5 | +210·5 | –0·875 |
| 0 | 78·5 ,, | | | | |
| 8 | 72·0 ,, | – 6·5 | – 7·0 | +211·0 | –0·875 |
| 0 | 79·0 ,, | | | | |
| 8 | 72·5 ,, | – 6·5 | – 7·0 | +211·5 | –0·875 |
| 0 | 79·5 ,, | | | | |
| 12 | 70·0 ,, | – 9·5 | –10·5 | +212·5 | –0·875 |
| 0 | 80·5 ,, | | | | |
| 12 | 70·5 ,, | –10·0 | –10·5 | +213·0 | –0·875 |
| 0 | 81·0 ,, | | | | |
| 16 | 69·0 ,, | –12·0 | –14·0 | +215·0 | –0·875 |
| 0 | 83·0 ,, | | | | |
| 20 | 71·0 ,, | –12·0 | –17·5 | +220·5 | –0·875 |
| 0 | 88·5 ,, | | | | |

*Remarks on Experiments II and III.*

From the third column of Experiment II may be gathered that the resistance of the cobalt *decreases* up to a certain degree of loading, and then begins to increase. The maximum decrease becomes less and less, at first rapidly, and then more slowly as the permanent strain due to the loading becomes greater and greater until a load of 18 kilos.* had been employed. The point of loading at which the maximum decrease occurs becomes higher and higher, gradually increasing from 8 kilos. to about 13 kilos.

* This does not include the stress due to the weight of the lever.

The sixth column shows that the *temporary* alteration of resistance is of the nature of a *decrease*, but the decrease becomes less and less as the permanent strain increases, at first rapidly, and afterwards more slowly, until the load of 18 kilos. has produced its permanent effect. Moreover, we learn from this column that when a load of 12 kilos. had been employed the temporary effect per kilogram is always greater for the highest load than for the smaller ones, so that for the loads 16, 18, and 20 kilos., *when employed for the first time*, we get about twice the temporary decrease per kilogram which is obtained with the loads 2 and 4 kilos. Experiment III, however, teaches us that ultimately, when all the loads have been applied a great number of times, *the temporary decrease is exactly proportional to the load* in the case of the loads 4, 8, 12, 16, and 20 kilos., nor is there any sign, as was the case with nickel, that the decrease of resistance would ultimately be changed to increase when the stress was increased beyond a certain limit. The greatest total stress on the strip, including that caused by the weight of the lever itself, was 1860 kilos. per square centimetre, whereas with nickel the point of loading where the above-mentioned limit was reached, was about 1500 kilos. per square centimetre.* It would seem probable that there is a limiting stress beyond which, as in nickel, the resistance begins to increase with the load, but it is evident from what has been said that this limiting stress is much higher for cobalt than nickel.

From the last values recorded in the sixth column of Experiment III it was calculated that the *decrease* of resistance per unit produced by a stress of 1 gram per square centimetre at the temperature of 16° C. is $386{\cdot}8 \times 10^{-12}$. The ratio of the decrease of resistance per unit to the increase of length per unit† is 0·703, and, if we assume the ratio of lateral contraction to linear elongation to be 0·250, the ratio of the decrease of *specific* resistance per unit to the increase of length per unit of the stress is 2·203. All the values just given are much less than the corresponding ones in the case of nickel.

With the cobalt in the unannealed state temporary traction also produced *decrease* of resistance, but, as might be expected from what has been said above with reference to the effect of permanent strain, the amount of decrease per unit was less than with the annealed metal.‡ The decrease of resistance per unit produced by a stress of

* *Loc. cit.*, p. 60, where the stresses given should be increased by that caused by the weight of the scale-pan if the total stress on the wire is, as in this case, required.

† $\frac{\Delta R}{R} : \frac{\Delta l}{l}$, where R is the resistance and $\Delta R$ is the decrease of resistance which results when the length, $l$, is increased to $l + \Delta l$.

‡ Notice the similarity in this respect between cobalt and nickel. *Loc. cit.*, p. 61.

1 gram per square centimetre was for the unannealed cobalt $242 \cdot 3 \times 10^{-12}$. The ratio of the decrease of resistance per unit to the increase of length per unit is 0·486, and the corresponding ratio in the case of *specific* resistance is 1·986.

Not only is cobalt remarkable for having, like nickel, its resistance decreased by longitudinal traction, in spite of the increase of length and diminution of section which is caused by the stress, but it also presents a peculiarity not seen in nickel or indeed in any of the other metals hitherto examined, namely, the *extreme* persistence with which the same load when applied again and again continues to produce permanent increase of resistance. With few metals is this persistence anything like so noticeable with such stresses per square centimetre as have been here employed, for we may observe from the last two experiments that though a load of 22 kilos. had been twice used on the lever, and afterwards a long rest given to the strip, 20 kilos., after having been put on and taken off fifteen times, still continued to produce permanent increase of resistance.* Even 16 kilos. continued to produce a permanent effect, so that it would be only after a very large number of loadings and unloadings that the increase of resistance on taking off the load would be equal to the decrease of resistance on putting on the load. The permanent increase of resistance caused by the above-mentioned loads also was greater the longer the time during which the stress was maintained.†

### *The Effect of Permanent Longitudinal Extension on the Specific Resistance of Cobalt.*

We have seen that cobalt behaves like nickel as far as the effect on the specific resistance of temporary longitudinal stress is concerned, and that both iron and nickel‡ are decreased in specific resistance by moderate longitudinal strain. This it appears is the case with cobalt also. The distance between the points where the copper wires at the upper and lower extremities of the cobalt strip were soldered, was before stretching 49·8 cm. and after the stretching 50 cm. The specific resistance before the stretching was $2289 \times 10^{-8}$, and after the stretching $2231 \times 10^{-8}$, so that there was a *decrease* of specific resistance of 2·6 per cent. for a permanent lengthening of 1·8 per cent. The permanent decrease of specific resistance per unit divided by the permanent increase of length per unit, is for iron 0·02, for cobalt 1·44, and for nickel 2·37; so that the permanent

* This was afterwards found to be the case when the same load had been put on and taken off some fifteen times more.

† This "running down" is also explained with other metals, but not to the same extent, as regards persistency with such comparatively small stresses per square centimetre.

‡ *Loc. cit.*, p. 100.

decrease of specific resistance as well as the temporary decrease is greater with nickel than with cobalt.

*The Effect of Longitudinal Traction and of Longitudinal Magnetisation on the Thermo-electric Properties of Cobalt.*

It will be seen that contrary to the expectation of myself, who had regard to the relationship which apparently exists between the "rotational coefficient" of Hall and the alteration of specific resistance caused by traction, cobalt behaves like nickel and not like iron. I now, therefore, turned to examine the effect of traction on the thermo-electric properties of the metal, for the purpose of ascertaining whether the strip would act in respect to these properties like iron or nickel. According to Bidwell* cobalt acts like iron, but it appears that this experimenter did not subject his bar of cobalt to traction but to *torsion*, and finding that copper under torsion behaved similarly to copper under longitudinal traction, assumed that cobalt would do so likewise. The above-mentioned assumption is hardly, I think, justifiable, and the following experiments show that cobalt is altered by traction in a manner similar to nickel, *provided the metals are not at the same time under the influence of any magnetising stress.*

*Experiment IV.*

The two strips of cobalt in the unannealed condition were clamped together at their centres, the clamp projecting to a distance of about 3 inches from and at right angles to the strips. One of the strips could be stretched as before by means of the lever, and insulated copper wire soldered near the lower extremities of the two strips served to connect them with the galvanometer. The clamp was then heated at the extremity furthest away from the strips, and the heat conducted along the clamp to the strips was such that in a short time a temperature, as judged roughly by the touch of about 60° C., was attained, stress of moderate amount was then put upon the lever, and this caused a current from stretched to unstretched through the heated junction: consequently *stretched cobalt is thermo-electrically positive to unstretched cobalt.* As soon as the needle of the galvanometer was fairly steady, the stress was removed and a deflection in the opposite direction ensued. The temporary stretching and unstretching were repeated several times, but always with the same result as regards the direction of the deflection. The unannealed cobalt therefore under mechanical stress behaves thermo-electrically like nickel.†

* "Phil. Mag.," April 1884, p. 261.

† In this experiment the strips were under the influence of the earth's vertical magnetic stress, but this last is so much smaller than that due to the helix, that I have not deemed it necessary to take it into account.

*Experiment V.*

The strips were now dismounted and the same one as had been used before was placed in the axis of a magnetising helix,* especially designed to prevent the heat of the helix from reaching the metal to be magnetised. The two ends of the strip, which projected about 8 inches from either end of the helix, were connected with the galvanometer, and the clamp before used was now at one end of the helix and just outside. The temperature was raised to about 60° C., and as soon as the galvanometer needle had become fairly steady the helix was excited by a single Leclanché cell.† A deflection of the galvanometer needle at once indicated a current from unmagnetised cobalt to magnetised cobalt through the hot junction, and proved that *longitudinally magnetised cobalt is negative to unmagnetised cobalt.* The unannealed cobalt, therefore, under magnetic stress, behaves thermo-electrically in a manner similar to iron. The helix in this experiment was too far from the galvanometer to affect the latter directly, and a reversal of the magnetising current produced a thermo-electric current in the same direction as before. The magnetising force was in this case equal to $4\pi \times 90{\cdot}6 \times 0{\cdot}478 \times C$ in absolute units, where C expresses the magnetising current in absolute units. The electromotive force of the cell was 1·5 volts very nearly, and the resistance in circuit 1·8 ohms, consequently the value of C would be $\frac{1{\cdot}5 \times 10^8}{1{\cdot}8 \times 10^9}$ absolute units, and the magnetising force 43·9 absolute units.

This last result has an important bearing on the question whether Bidwell's explanation of Hall's phenomenon is correct, because, though unmagnetised cobalt is certainly rendered thermo-electrically positive by longitudinal mechanical stress, the case may be different when the metal is magnetised, as in Hall's experiment.‡

Nor indeed would it be safe to assume, without further experiment, that mechanical stress will produce the same effect either in nature or amount on the electrical resistance§ or on the thermo-electric properties of magnetised iron, nickel, and cobalt, as it does on the same metals when not under the influence of magnetic stress.

*Experiment VI.*

The strip of cobalt used in Experiments IV and V having been annealed, was tested as before for the effect of mechanical stress on

* For a description of this helix, designated as "the coil B," see *loc. cit.*, p. 136.

† One of the more recent kind, and which gives a fairly constant current.

‡ See Sir W. Thomson's paper on "The Effects of Stress on the Magnetisation of Iron, Nickel, and Cobalt," "Phil. Trans.," vol. 170, 1879.

§ I may not, therefore, be right in my conjecture (see "Note on Hall's Phenomenon," "Phil. Mag.," May 1884, p. 402) that in all probability the "Hall effect" on nickel will be diminished by raising the temperature to 100° C.

the thermo-electric properties of the metal. The heating was, however, in this case accomplished by means of an air-chamber, consisting of two concentric brass cylinders with a layer of water between them. The strips were placed, clamped together at their centres, in the axis of the chamber, the two extremities of each projecting about 8 inches from either end of the chamber; a thermometer was also placed with its bulb in the centre of the latter, and the temperature in the first instance raised to 100° C. When the needle of the galvanometer was at rest, a load of 8 kilos. was put on the lever, and after a space of 2 minutes had elapsed a deflection of three divisions of the scale resulted. This deflection again showed the *stressed metal to be positive to the unstretched*, and on the removal of the load the needle came back again to nearly its old position. Trials were made with several loads from 2 to 8 kilos., and always with the same result as regards the nature of the effect; the mean value of the deflection per kilo. being as nearly as could be judged 0·375 division of the scale. The electromotive force developed by the highest load was found to be 0·429 microvolt, and the electromotive force which would be produced by a stress of 1 gram per square centimetre would be $659 \times 10^{-9}$ microvolts, the temperature of one junction being at 100° C. and of the other about 16° C. The chamber was next permitted to cool down, first to 60° C., and afterwards to 42° C., and at both these temperatures the effect of the stress was found to be in the same direction as before, and though no attempt was made to measure the actual deflection, this was evidently diminished with the temperature.

Finally, it should be added that both in this experiment and in the two previous ones, the extremities of the strips and the clamps at the ends of the stressed strip were all well shielded from the source of heat. It would seem then that we have good reason for concluding that for any temperature between 16° C. and 100° C., cobalt, whether in the annealed or unannealed condition, is rendered by traction thermo-electrically positive to unstretched cobalt.*

### *The Effect of Excessive Loading on the Electrical Resistance of Hard Piano-steel.*

#### *Experiment VII.*

I have already shown† that for moderate amounts of stress the effect on the electrical resistance of piano-steel is of the same nature as the effect on iron, but, as according to Mr. H. Johnson,‡ the

* As I thought that want of purity might influence the result, Mr. J. M. Thomson of King's College kindly made an analysis of two small pieces of the metal, and informed me that they contained more than 98 per cent. of cobalt, no trace of nickel, and barely a trace of iron.

† *Loc. cit.*

‡ "The Electrician," May 17th, 1884.

specific resistance of hard piano-steel wire is temporarily diminished by *very considerable* longitudinal traction, I arranged a pair of hard piano-steel wires in the same manner as the nickel wires, of which already mention has been made, and proceeded to test one of them in the usual manner, expecting that whilst moderate stress would increase the specific resistance, excessive stress would diminish it. The loading was accomplished by means of the lever before used, and the results are given below :—

| Permanent load on the lever in kilos. | Temporary load in kilos. | Increase of resistance produced by loading in divisions of the platino-iridium wire. | Increase of resistance per kilo. on the lever. |
|---|---|---|---|
| 1* | 4 | 160 | 40·00 |
| 1 | 6 | 242 | 40·33 |
| 7 | 6 | 240 | 40·00 |
| 13 | 6 | 242 | 40·33 |
| | | Mean ........ | 40·17 |

It will be seen that the *increase* of resistance produced by the loading is proportional to the load throughout. The diameter of the wire was 0·08246 cm., and the greatest total load on the wire was equal to 102 kilos., or 2 cwts. The greatest stress per square centimetre was above 19,000 kilos., and only a little short of the breaking stress. From the above results was deduced that the increase of resistance per unit produced by a stress of 1 gram per square centimetre, was $1620 \times 10^{-12}$, and this number so nearly agrees with those obtained for the previously used specimens of piano-steel, that it was not considered necessary to determine the value of "Young's modulus" and of the simple rigidity, in order to prove that, as in soft iron, the *specific* resistance is *increased*, not only when moderate stresses are employed *but also for stresses close to the breaking load.*† This last experiment, however, confirms the fact mentioned in an earlier paper,‡ that the electrical resistance of steel is less increased than that of iron, not only per gram stress on the square centimetre, but also per unit increase of length.

* This is the load due to the weight of the lever itself.

† I afterwards found that Mr. Johnson must have miscalculated the amount of *temporary lengthening* produced by the load used by him, as he gives it as 3 per cent., though the wire was not loaded beyond the limits of elasticity. This last is an *impossible* result, as the greatest tensile strength of any piano-wire does not admit of a temporary elongation of more than 1·6 per cent. without breaking.

‡ "Proc. Roy. Soc.," vol. 26, p. 401.

*The Effect of Longitudinal Traction on the Electrical Resistance of Magnesium.*

Cobalt and nickel have been found to decrease in resistance when subjected to moderate longitudinal traction, nor does it appear* that this abnormal behaviour is in any way connected with the magnetic properties of these metals. Nevertheless, it seemed desirable to find, if possible, some metal which, possessing much feebler magnetic properties, would exhibit similar conduct. Now, judging from the apparent relationship between the alteration of specific resistance produced by traction and the "Hall effect," that magnesium might be found to be such a metal, I obtained from Messrs. Matthey and Johnson about 60 feet of magnesium wire, and examined it with the above-mentioned object in view.

*Preliminary Determinations of the Value of "Young's Modulus," Simple Rigidity, Density, &c.*

"Young's modulus" was, in the first instance, determined by the method of longitudinal vibrations, a length of 550 cm. being under examination. The wire was stretched on a long wooden box, and precautions taken which will be fully described in a future communication to the Society, to avoid certain sources of error incidental to this method. The results obtained with the syren were quite as accordant with each other as those got with the cobalt strip, and from these and the value of the density obtained in the manner presently to be described, was deduced a value of "Young's modulus" of $437·3 \times 10^6$ grams per square centimetre.

The simple rigidity of the wire was determined by the method of torsional vibrations in the manner described in a former portion of this memoir,† and proved to be $172·3 \times 10^6$ grams per square centimetre.

Some little difficulty was experienced in finding the density of the magnesium, as when the wire was immersed in water a very large number of minute bubbles of gas—evidently a consequence of chemical action—made the apparent mass in water from 10 to 20 per cent. less than it ought to have been. Most of these bubbles could be shaken off by merely moving the wire twice or thrice backwards and forwards through the water, but in a very few seconds they collected again and rendered it evident that no reliable determination of the density could be obtained in this way. As there was not at hand any liquid which might be suitably used in place of the water, the density was ascertained from the length, diameter, and mass of three separate lengths of the wire. The diameter of each of these pieces was mea-

* "Phil. Trans.," vol. 174, 1883, pp. 61, 62.

† *Loc. cit.*, p. 24.

sured at ten different places equidistant from each other by a gauge graduated to $\frac{1}{100}$th of a millimetre, and capable of measuring by estimation to $\frac{1}{1000}$th of a millimetre. The accuracy of the gauge had been repeatedly tested on previous occasions, and could be depended upon at least to $\frac{1}{1000}$th of the diameter of the wire: nor would any error of consequence be introduced in the determinations of either the length or mass.

The following were the results:—

| Number of piece. | Length in centimetres. | Mean diameter in centimetres. | Mass in grams. | Density at 20° C. |
|---|---|---|---|---|
| 1 | 162·5 | 0·08736 | 1·6910 | 1·736 |
| 2 | 123·0 | 0·08671 | 1·2742 | 1·754 |
| 3 | 131·5 | 0·08723 | 1·3670 | 1·740 |
| Mean ........ | | 0·08710 | .. | 1·743 |

The probable error in the determination of the density in this way would therefore appear to be 0·2 per cent. But values of "Young's modulus" obtained by the method of longitudinal vibrations are apt to be slightly too high in the case of wires in consequence of slight yielding of the supports at either end of the wire.* It was therefore deemed advisable to employ also the static method, and accordingly a pair of wires were suspended and examined in the manner already described in Part I of this memoir, and with the same precautions to avoid error.† "Young's modulus" as thus obtained proved to be $424{\cdot}3 \times 10^6$ grams per square centimetre. It was impossible, however, in this instance to have any but a comparatively small load permanently on the wire, and in such a case the result is apt to be too low to a slight extent. We may, I think, then, find a very near approach to the true value by taking the mean between the values got by the two methods: this mean is $430{\cdot}8 + 10^6$ grams per square centimetre, and is, I should say, certainly less than 1 per cent. in error.

From "Young's modulus" and the simple rigidity the ratio of lateral contraction to longitudinal extension can be calculated; this ratio would be—

$$\frac{430{\cdot}8 \times 10^6}{2 \times 172{\cdot}3 \times 10^6} - 1,$$

* It might be thought that any kind of yielding would depress the pitch of the wire, but the mathematical investigations of Lord Rayleigh as given in his "Theory of Sound," vol. i, p. 161, show that with *transverse* vibrations there would be in the case before us an increase of pitch. Rayleigh's investigations will equally apply, as far as the point in question is concerned, to longitudinal vibrations.

† *Loc. cit.*, pp. 2–4 inclusive.

or $$0{\cdot}2505.$$

The bulk-modulus can also be determined from "Young's modulus" and this last ratio, and is—

$$\frac{430{\cdot}8\times10^6}{3(1-2\times0{\cdot}2505)}$$

$$=\quad 287{\cdot}6\times10^6 \text{ grams per square centimetre.}$$

Now it has been shown in a recent communication* to the Royal Society that the bulk-modulus can be calculated from the thermal capacity per unit volume by the formula—

$$e_v=2071\times10^6\times C_v^{\frac{7}{3}},$$

where $e_v$ is the bulk-modulus and $C_v$ the mean thermal capacity per unit volume between 0° C. and 100° C. According to Regnault the thermal capacity per unit mass is 0·2499, and according to Kopp it is 0·245.† The mean of these two numbers is 0·2480, and the thermal capacity per unit volume is therefore 0·2480 × 1·743, or 0·4323. From the above formula, therefore, we obtain—

$$e_v=2071\times10^6\times0{\cdot}4{\cdot}323^{\frac{7}{3}}$$

$$=292{\cdot}7\times10^6.$$

This number does not differ from that obtained by observation by so much as 2 per cent., and considering the difficulties which are in the way of getting correct values of the bulk-modulus, we may regard the agreement of the observed and calculated values of $e_v$ as sufficiently satisfactory.

*Arrangement of the Magnesium Wire for Observations on the Alteration of Resistance produced by Longitudinal Traction.*

*Experiment VIII.*

A pair of magnesium wires were arranged for an examination of the effect of longitudinal traction on the electrical resistance of the metal in the same manner as the nickel wire before mentioned, but, as it was desirable to have the permanent load as light as possible in order to avoid trespassing beyond the limits of elasticity, the scale-pan was dispensed with and the weights were suspended to a small hook‡ by string so that at the outset the permanent load on the wire only amounted to ½ kilo. When a sufficient rest had been allowed to

* "Proc. Roy. Soc.," No. 232, 1884.

† Clarke's "Constants of Nature," Smithsonian Miscellaneous Collection, No. 276, p. 15.

‡ *Loc. cit.*, p. 58, fig. 10.

enable the pair of wires to attain a constant resistance-ratio, various amounts of temporary stress from ½ to 2 kilos. were employed. The results are given below:—

| Permanent load on the wire in kilos.* | Temporary load in kilos. | Temporary alteration of resistance in divisions of the platinum-iridium wire. | Temporary alteration of resistance per kilo. |
|---|---|---|---|
| ½ | ½ | 4·4 | 8·8 |
| ½ | 1 | 10·8 | 10·8 |
| ½ | 1½ | 19·5 | 13·0 |
| ½ | 2 | 31·4 | 15·7 |
| 2 | ½ | 4·4 | 6·8 |

The wire completely recovered itself when each of the temporary loads was removed, and yet it will be noticed that the alteration of resistance per kilo.† varies largely with the load, so much so, indeed, that with a temporary load of 2 kilos. the temporary alteration per kilo., which is of the nature of *increase* on loading, was nearly double that when only ½ kilo. was employed for the temporary load. This marked increase of alteration of resistance per kilo. with the increase of the temporary load does not depend upon the amount of permanent stress, as we obtain the same alteration for ½ kilo. when the permanent load is ½ kilo. as we do when the permanent load is 2 kilos., but at the same time it should be observed that with the permanent load of 2 kilos. the *first* effect both of loading and unloading with ½ kilo. was considerably greater‡ than that which took place after three loadings and unloadings with the ½ kilo.§ The results given above undoubtedly point to imperfect elasticity due to the rotation of the molecules about their axes, for though the wire recovered its original resistance on the removal of the load, this is evidently due to the slight shock caused by unloading.||

### *Experiment IX.*

In order to examine more fully the relationship which might exist between the alteration of resistance and the alteration of length caused by temporary traction, the wire used in determining the value

* Weight of clamp, hook, &c., included.

† The means of ten closely according trials with each load.

‡ More than twice as great.

§ After this the effect remained constant.

|| With some metals a marvellously small agitation suffices to make the molecules spring back to their original position after they have been permanently deflected from their positions by mechanical or other stress.

of "Young's modulus" by the method of static extension was tested with nearly the same loads, both temporary and permanent, as in the last experiment, with the following results:—

| Permanent load in kilos. | Temporary load in kilos. | Temporary alteration of length in half-millimetres. | Temporary alteration of length per kilo. |
|---|---|---|---|
| $\frac{1}{2}$ | $\frac{1}{2}$ | 2·70 | 5·40 |
| $\frac{1}{2}$ | 1 | 5·49 | 5·49 |
| $\frac{1}{2}$ | $1\frac{1}{2}$ | 8·29 | 5·53 |
| $\frac{1}{2}$ | 2 | 11·41 | 5·76 |
| $1\frac{1}{2}$ | $\frac{1}{2}$ | 2·37 | 4·74 |
| $2\frac{1}{2}$ | $\frac{1}{2}$ | 2·37 | 4·74 |
| 1 | $\frac{1}{2}$ | 2·54 | 5·08 |

The numbers given in the third column are the means of several trials and, with the exception of the last two, require a slight correction, inasmuch as it was evidently impossible with such a small permanent load as $\frac{1}{2}$ kilo. to obtain a sufficiently straight wire.* The correction, however, can be easily applied, for we see that when the permanent load is equal to $1\frac{1}{2}$ kilos. a temporary load of $\frac{1}{2}$ kilo. produces precisely the same temporary elongation as when the permanent load is $2\frac{1}{2}$ kilos., or, in other words, $1\frac{1}{2}$ kilos. must have sufficed to make the wire straight. Thus with a permanent load of $\frac{1}{2}$ kilo. the apparent increase of length caused by the mere straightening of the wire is $2·70-2·37$, or 0·43 when $\frac{1}{2}$ kilo. is the temporary load, and will be $0·43+2·53-2·37$, or 0·59 when the temporary load is either 1 kilo. or greater than 1 kilo. Making the above corrections, and placing side by side the alteration of length and the alteration of resistance produced by each additional $\frac{1}{2}$ kilo., we obtain as follows:—

| Number of $\frac{1}{2}$ kilos. | Temporary alteration of resistance for each successive $\frac{1}{2}$ kilo. | Temporary alteration of length for each successive $\frac{1}{2}$ kilo. |
|---|---|---|
| 1 | 4·4 | 2·37 |
| 2 | 6·4 | 2·63 |
| 3 | 8·7 | 2·80 |
| 4 | 11·9 | 3·12 |

We may notice that though, in consequence of imperfect elasticity,†

* A matter of no importance in the electrical experiments.

† The recovery of length was as complete as the recovery of resistance had been on the removal of the stress, and this is no doubt due to the cause previously mentioned.

the temporary alteration of length increases in greater proportion than the load, this increase of effect is very much less than is the case when the alteration of resistance is concerned, the difference between the first and last numbers of the third column being only 31 per cent. as compared with the 170 per cent. difference between the first and last numbers of the second column.

It has been proved that longitudinal traction on the whole causes *increase* of resistance, but this increase is *less* than can be accounted for by mere change of dimensions, provided that the temporary stress used be sufficiently small. In the present instance it may be assumed that for any temporary stress not exceeding $\frac{1}{2}$ kilo. we shall barely enter into the region where "Hooke's law" no longer holds good,* and that up this limit of loading the increase of resistance and of length will, within the limits of errors of observation, be proportional to the load, since, were it otherwise, there could not be the accordance which there is between the value of "Young's modulus" as determined by the statical and dynamical methods.† If, then, we take 4·4 divisions of the platinum-iridium wire to represent the temporary increase of resistance produced by a load of $\frac{1}{2}$ kilo., we gather that the increase of resistance due to a stress of 1 gram per square centimetre is $1841 \times 10^{-12}$ per unit. In calculating the alteration of resistance per unit, resulting from increase of length, we must take the value of "Young's modulus" obtained by using the statical method, for the alteration of resistance is necessarily determined by this method. If we do so we find that the ratio of the increase of resistance per *unit* to the increase of length per unit is 0·7813. The mere change of dimensions, however, would cause an increase of resistance of 1+25, where 0 is the ratio of lateral contraction to longitudinal extension, and may be taken as equal to 0·2501; so that on the whole we have a *decrease* of the *specific* resistance per unit, equal to 1·5002−0·7813, or 0·7189. With aluminium also it has been shown‡ that there is a *decrease* of *specific* resistance per unit; but this is of small amount, namely, 0·420 for the unannealed, and 0·262 for the annealed metal. We may say, then, that though magnesium does not agree with nickel and cobalt in having its resistance decreased—in spite of change of dimensions—it does agree with these metals and with aluminium in having its *specific* resistance *decreased* by longitudinal traction of small amount.

The question next arises, shall we, passing the limit of temporary stress up to which "Hooke's law" holds good, eventually find the *decrease* of specific resistance changed into *increase* when the tem-

* See *loc. cit.*, pp. 12, 13.

† The temporary elongation produced by $\frac{1}{2}$ kilo., namely, 2·37 half-millimetres, was employed in calculating the former of the two values.

‡ *Loc. cit.*, p. 52.

porary stress is comparatively large? The answer must be in the affirmative, for, as we have seen, the alteration of resistance increases with the load much more largely than the alteration of length: this is shown in the next table.

Table I.

| Limits of temporary load in kilos. | Increase of resistance per unit divided by the increase of length per unit. | Alteration of specific resistance per unit divided by the increase of length per unit. + signifies increase of specific resistance. |
|---|---|---|
| 0—$\frac{1}{2}$ | 0·7813 | −0·719 |
| $\frac{1}{2}$—1 | 1·028 | −0·472 |
| 1—$1\frac{1}{2}$ | 1·307 | −0·193 |
| $1\frac{1}{2}$—2 | 1·605 | +0·105 |

It would appear, then, at first sight, that magnesium and nickel behave in a somewhat similar manner as regards the effect of stress on their specific electrical resistance, for with nickel the decrease of resistance is changed to increase when the stress has passed a certain limit. Closer examination, however, does not justify this view, for with nickel the change from decrease to increase is conditioned by the amount of the permanent load, so that if say 6 kilos. be the limiting stress, and we maintain this stress permanently, an additional kilo. will always produce increase of resistance, though this load of 1 kilo. be taken off and put on *any number of times*, whilst with magnesium, if we regard 2 kilos. as the limiting stress, and allow this load to remain on, an additional $\frac{1}{2}$ kilo. will only produce a temporary *increase* or a temporary *decrease* of specific resistance when put on and taken off respectively for *the first time*.

*The Alteration of the Electrical Resistance of Platinum-iridium produced by Longitudinal Traction.*

Platinum-iridium plays such an important part in the construction of standards of length and of electrical resistance, that having a length of wire made of the alloy sufficient for my purpose, I resolved to test its elasticity, and the change of electrical resistance due to stress.

*Preliminary Determination of the Value of "Young's Modulus," Simple Rigidity, Density, &c.*

The alloy was specially prepared for me by Messrs. Johnson and

Matthey, and an analysis made by them of a similar specimen, not, however, drawn into wire, yielded the results given below.*

| | Proportion. |
|---|---|
| Platinum-iridium at 10 per cent.. | 99·33 |
| Iridium in excess .............. | 0·23 |
| Rhodium .................... | 0·18 |
| Ruthenium.................... | 0·10 |
| Iron......................... | 0·06 |
| | 99·90 |

The density at 0° C., calculated from this analysis, was 21·510, and according to MM. Deville and Mascart the coefficient of thermal expansion between 0° C. and 16° C. is 0·00002541.

As it was not considered advisable to bend the wire so as to form it into a coil suitable for finding the density in the ordinary way, the latter was calculated from the mass, length, and diameter. The length of the wire was 61·90 cm., the mass 22·088 grams, and the diameter, as measured by the gauge at seven equidistant places, was as follows:—

| Number of place. | Diameter in centimetres. |
|---|---|
| 1 | 0·1454 |
| 2 | 0·1454 |
| 3 | 0·1453 |
| 4 | 0·1454 |
| 5 | 0·1453 |
| 6 | 0·1450 |
| 7 | 0·1453 |
| Mean ........ | 0·1453 |

From these data was deduced a density at 16° C. of 21·523, which value, considering the drawing to which the metal had been subjected, agrees very well with that calculated from the above analysis.

The value of "Young's modulus" was first determined by the static method in my usual way, and proved to be $2089 \times 10^6$ grams per square centimetre, and though the length of the wire operated upon was inconveniently small, the different trials agree very well with each other. The modulus was next determined by the method of longitudinal vibrations, the wire, which was sufficiently stout and rigid

* "Nature," August 7, 1879, p. 343.

for the purpose, being held by the finger and thumb in the centre, and rubbed with a resined glove. When rubbed, the wire yielded sometimes one note, and sometimes another about a semitone lower in pitch. Both these notes were fairly clear, and from the higher of the two a value for the modulus was deduced of $2276 \times 10^6$ grams per square centimetre, whilst from the lower was obtained a value which within the limits of error of observation was exactly equal to that got by the static method; so that we may regard $2089 \times 10^6$ grams per square centimetre as representing with fair accuracy* the value of "Young's modulus."

There was no difficulty in finding the value of the simple rigidity in the usual way, and this proved to be $724{\cdot}8 \times 10^6$ grams per square centimetre. From the above data the ratio of lateral contraction to longitudinal extension was calculated to be 0·441. The values of "Young's modulus" and of the simple rigidity are both high, and it is very remarkable that the 10 per cent. of iridium added to the platinum should have raised the former value more than 40 per cent.

*Arrangement of the Platinum-iridium Wire for Observations on the Alteration of Resistance produced by Longitudinal Traction.*

*Experiment X.*

We will now turn to the experiments on the alteration of resistance produced by longitudinal traction experiments, which it will be seen resulted in a complete surprise in more ways than one. In the first trials the wire was arranged in exactly the same manner as the steel and magnesium wires had been, and the lever used for applying the stress, but a German-silver wire was employed as the comparison-wire. With only a permanent stress, due to the weight of the lever, 2 kilos. put on or taken off the lever caused an alteration of resistance which required to be balanced by moving the sliding-piece 54·5 divisions, and when there was a permanent stress equivalent in all to 3 kilos. on the end of the lever, an additional kilo. on or off caused an alteration represented by 27·0 divisions, or almost exactly half the number of divisions which were required with twice the temporary load. Hence it was calculated that a stress of 1 gram per square centimetre produced an increase of resistance per unit of $3049 \times 10^{-12}$. The increase of resistance per unit divided by increase of length per unit was 6·368, and the increase of *specific* resistance per unit was 4·486. These results were very unexpected, inasmuch as all the other alloys which have been examined, namely, brass, German-silver, and platinum-silver are altered by stress in their electrical resistance far less than the pure metals of which they are composed,

* This value would seem to be correct within at least 2 per cent.

whereas here the increase of specific resistance produced by traction is nearly three times as great as with iron, which heads the list of those metals which show increase of resistance on loading.

### *Experiment XI.*

Under the above-mentioned circumstances, it was deemed to be advisable to test the platinum-iridium in another manner. In this case, instead of using German-silver as the comparison-wire, the following arrangement was made:—

To the centre of the wire was firmly fixed a brass clamp, which rested on a stout table, and was connected with one terminal of the galvanometer, the other terminal being as usual connected with the sliding-piece. The lower half of the wire, which passed through a small hole in the table, was stretched by means of the lever, whilst the upper half remained unstretched. Near the extremities of both halves were fixed other clamps, provided with terminal screws, which in each case were united as usual with one pole of a battery, and with a set of resistance coils joined to each other by the platinum-iridium wire traversed by the sliding-piece. With this arrangement it will be seen that the upper half of the wire served as a comparison-wire to the lower half. The results of this experiment were in fair accordance with those of the previous one, and still showed platinum-iridium to be considerably more increased in resistance by traction than any of the other metals.

### *Experiment XII.*

In order to remove any further doubt about clamping not being sufficient to make proper connexion between the various parts of the "bridge," a third experiment was tried, in which the platinum-iridium wire, with a German-silver wire as a comparison-wire, were arranged as in Experiment X, but now all connexions with the wire to be stretched were well soldered, and a long series of trials, extending over three days, was made with a view to not only confirm the results of Experiments X and XI, but also to bring out any fresh peculiarities which might exist. The main points to which it is well to call attention are shown in the last two series of trials given below, in which the permanent stress was that due to the weight of the lever itself.

It is noteworthy here that the resistance at first increases in greater proportion than the load, but when a certain limit of stress has been reached the ratio of the increase of resistance to the load producing it begins to diminish, until finally the last kilogram only produces the same alteration of resistance as the first. A similar state of things was perceived with wires made of other metals in the experiments

| Kilos. on the lever. | Temporary alteration of resistance in terms of the divisions of the *graduated* platinum-iridium wire. First series. | Temporary alteration of resistance, &c. Second series. | Mean alteration from the two series. |
|---|---|---|---|
| 1st kilo. | 23·0 | 23·5 | 23·25 |
| 2nd „ | 23·5 | 24·5 | 24·00 |
| 3rd „ | 29·5 | 29·5 | 29·50 |
| 4th „ | 32·0 | 33·5 | 32·75 |
| 5th „ | 35·0 | 29·0 | 32·00 |
| 6th „ | 27·0 | 28·0 | 27·50 |
| 7th „ | 23·0 | 26·5 | 24·75 |
| 8th „ | .. | 23·5 | 23·50 |

described in the previous portions of this memoir,* and, moreover, there is a like change in the elasticity,† but with platinum-iridium the effect, as far as alteration of the resistance is concerned, is more marked than is the case with other metals. Equally noteworthy is it that at the third kilogram there is a *sudden* increase in the temporary alteration of resistance produced by the load, and a like phenomenon is plainly discernible in the above-mentioned previous experiments. Moreover, the stress which produces this sudden increase is certainly not far from the stress which produces the first sudden leap in the value of the ratio of the *permanent* alteration of resistance to the load, when the annealed wire is stretched for the first time;‡ nay, more, a careful examination of Experiment VII§ shows undoubted evidence of the existence of the same number of critical points where *temporary* alteration is concerned, as there are in the case of *permanent* extension.

Finally, it must be added, that if we take the mean effect produced by all the loads on the resistance of the wire, we obtain an increase of resistance which is exactly equal to that already recorded in Experiment X, and therefore we must regard the comparatively large increase of resistance of platinum-iridium caused by traction as a well-established fact.||

* *Loc. cit.*, p. 50, where by taking the alteration of resistance caused by consecutive loads of 2 kilos. each, this can be plainly discerned.

† *Loc. cit.*, p. 16.

‡ Compare Experiments VII and XXIII, *loc. cit.*, pp. 50, 82. As regards Experiment XXIII, it should be remarked that more recent observations have shown that there is a critical point at the third kilogram (fifth kilogram if we include the weight of the scale-pan itself), and that here therefore we must look for the first critical point and not at the eighth kilogram (tenth kilogram including the weight of the scale-pan), where is the *second* critical point.

§ *Loc. cit.*, p. 50.

|| This comparatively large increase of resistance produced by traction is rather against the use of platinum-iridium in the construction of standard resistance coils.

*The Effect of Longitudinal Traction on the Thermo-electric Properties of Platinum-iridium.*

*Experiment XIII.*

The above-mentioned large increase of resistance resulting from the temporary traction of platinum-iridium, together with the apparent relationship between the effect of mechanical stress on the thermo-electric properties of metals, and that on the specific resistance, rendered it probable that stress would act on the thermo-electric properties of iron and platinum-iridium similarly as regards nature, but with greater intensity with the latter metal than with the former, but here, again, a surprise was met with, for when the wire was tested in the same manner as the cobalt had been, the *unstretched* platinum-iridium was found to be *positive* to the *temporarily stretched* metal, and therefore the alloy is affected by stress, thermo-electrically, in a manner similar to *nickel.* Thus we see that, though these new experiments would in the case of cobalt and magnesium largely confirm us in our opinion respecting the above-mentioned relationship, it is quite the contrary in the case of platinum-iridium. In the next table will be found drawn up the results obtained by Hall, Bidwell, and myself.

Hall says of the numbers in the second column: "I cannot vouch for the quantities within 50 per cent., but I think I can vouch for the direction of the effect." Bearing this statement in mind, and the difficulties which lie in the way of obtaining accurate values for the ratio of lateral contraction to longitudinal extension, which difficulties will affect the numbers in the fourth and fifth columns, one cannot help being struck with the fact that with most of the metals the *order* of the "rotational coefficients" is the same as that of the alteration of specific resistance caused by traction. Cobalt and platinum are, however, conspicuous exceptions, but with regard to the former metal it has been already observed, and of course the same observation would apply equally to nickel and iron, that longitudinal traction might produce different effects in the magnetised and unmagnetised metals. The exception furnished by platinum cannot be thus accounted for, nor does it seem fair to attribute the discrepancy either to errors of observation or to difference in the purity of the specimens examined by Hall and myself respectively.* In the fifth column is given the difference between the alteration of the specific resistance of lead by traction, and that of the other metals, and, with the exceptions just mentioned,† it may be fairly said that, within the errors of

* The specimen of platinum used by myself was obtained from Messrs. Johnson and Matthey as chemically pure.

† I ought to remark here that according to Bidwell the "Hall effect" in aluminum is +. In a trial made by myself on the pure specimens of aluminium in

Table II.

| Metal. | "Rotational coefficient."* | Direction of thermo-electric current.† | Alteration of specific resistance per unit divided by increase of length per unit.‡ | Ditto. −1·613 |
|---|---|---|---|---|
| Iron | + 78·0 | + | +2·618 | + 1·005 |
| Steel | .. | + | +2·082 | + 0·469 |
| Cobalt | + 25·0 | − | −2·203 | − 3·816 |
| Zinc | + 15·0 | + | +2·113 | + 0·500 |
| Lead | 0 | 0 | +1·613 | 0 |
| Tin | − 0·2 | − | +1·630 | + 0·017 |
| Brass | − 1·3 | − | +0·166 | − 1·447 |
| Platinum | − 2·4 | − | +2·239 | + 1·626 |
| Gold | − 6·8 | − | | |
| Silver | − 8·6 | − | +1·617 | + 0·004 |
| Copper | − 10·0 | − | +1·005 | − 0·382 |
| Aluminum | − 50·0 | + | −0·420 | − 2·033 |
| Magnesium | − 50·0 | − | −0·733 | − 2·346 |
| Nickel | −120·0 | − | −8·860 | −10·473 |
| German-silver | — | − | +0·226 | − 1·387 |
| Platinum-silver | — | − | +0·624 | − 0·989 |
| Platinum-iridium | — | − | +4·486 | + 2·873 |

observation to which the numbers in this column are liable to be affected, the signs are here the same as those in the second column.

As regards the relationship between the alteration of specific resistance by traction and that of the thermo-electric qualities of the metals due to the same cause, it may be seen by comparing the third and fifth columns, that out of sixteen different metals, pure and alloyed, the signs in the two columns are decidedly the same in eleven instances, are decidedly different in three instances, and are dubiously so in two instances.

It has been noticed§ that if the density of a substance be denoted by $\Delta$, and A represent the atomic mass, so that the difference between the centres of adjacent molecules be proportional to $\left(\frac{A}{\Delta}\right)^{\frac{1}{3}}=\alpha$, say,

my possession, the effect of traction on the thermo-electric properties of the metal seemed to be the same in direction as that given, and for which Bidwell is my authority, but the effect was very slight, and I am not now quite certain whether a less stress than was then applied would not give an opposite result.

* A + sign in this column signifies that the effect is in a direction the same as that which the conductor itself bearing the current would follow if free to move across the lines of magnetic force (see "Nature," Nov. 10, 1881, p. 46).

† A + sign in this column signifies that the direction of the thermo-electric current is from *unstretched* to *stretched* through the *hot junction*.

‡ A + sign in this column signifies *increase* of resistance.

§ *Loc. cit.*, p. 32.

$e \times \alpha^7$ is, with most metals, a constant, where $e$ denotes "Young's modulus." Taking the mean of the values of $e$ and of $\Delta$ for cobalt in the annealed and unannealed conditions, we have $\alpha = 1{\cdot}927$, and $e \times \alpha^7 = 1886 \times 10^8$. For magnesium $\alpha = 2{\cdot}399$, and $e \times \alpha^7 = 1969 \times 10^8$.

In the next table will be found collected together most of those results of the present inquiry which can be expressed by numbers.

It has been suggested with regard to the method of finding the effect of strain on the resistance, that unless the strain was fairly uniform, thermo-electric effect might have to some extent vitiated the results. It will be seen, however, that the strain must have been fairly uniform, and even if there had been considerably more lack of uniformity than actually existed, the small change which can be wrought by stress and strain in the thermo-electric power of any of the metals hitherto used, would preclude the possibility of any appreciable vitiation. Further, in many cases, very different lengths of the same wire were tested and found to yield the same results, which would not have been the case had the strain on the connexions, a point also suggested for consideration, introduced error.

## *Summary.*

1. The electrical resistance of cobalt, like that of nickel, is temporarily decreased by temporary longitudinal traction. Whether the decrease of resistance would be changed to increase, as it is with nickel, by a greater amount of stress, has not yet been ascertained, but should this be the case, the magnitude of the stress per unit area which would suffice for the purpose, must be much greater with cobalt than with nickel.

2. Permanent extension and rolling diminishes with cobalt as with nickel, the effect of longitudinal traction alluded to in 1.

3. Cobalt is remarkable for the extreme persistence with which the same load, when applied again and again, continues to produce permanent increase of resistance.

4. Moderate permanent extension decreases permanently with cobalt as with nickel and iron, the *specific* resistance.

5. Temporary longitudinal traction renders cobalt temporarily positive as regards its thermo-electrical qualities to cobalt not under traction, provided there is no magnetic stress acting at the same time.

6. Temporary longitudinal magnetic stress renders cobalt temporarily negative as regards its thermo-electrical qualities to cobalt not under magnetic stress, provided there is no mechanical stress acting at the same time.

7. The effect of temporary longitudinal traction, even when carried to very great excess, is to increase the resistance of unannealed piano-steel; and this increase, though less than with iron, both for unit

Table III.

| Metal. | Condition. | Density. | "Young's modulus" in grams per sq. cm. | "Simple rigidity" in grams per sq. cm. | Specific resistance, *i.e.*, resistance in ohms of 1 c.c. between opposing forces. | Alteration of resistance per unit produced by a longitudinal stress of 1 grm. per sq. cm.* | Alteration of resistance per unit divided by increase of length per unit. | Alteration of specific resistance per unit divided by increase of length per unit. |
|---|---|---|---|---|---|---|---|---|
| Cobalt ..... | Unannealed. | 8·231 | $2005 \times 10^{6}$ | .. | $2450 \times 10^{-8}$ | $-\ 242{\cdot}3 \times 10^{-12}$ | −0·486 | −1·986 |
| Cobalt ..... | Annealed... | 8·259 | 1817 | .. | 2289 | − 386·8 | −0·703 | −2·203 |
| Magnesium . | Unannealed . | 1·743 | 430·8 | $172{\cdot}3 \times 10^{6}$ | 565 | +1841 | +0·781 | −0·719 |
| Platinum-iridium | Unannealed . | 21·523 | 2089 | 724·8 | 2830 | +3049 | +6·368 | +4·486 |

* A + sign in this and the next two columns signifies *increase* of resistance on the *application* of stress.

stress per square unit of area and per unit temporary increase of length, is much greater than can be accounted for by changes in the dimensions of the steel.

8. The electrical resistance of magnesium is temporarily increased by temporary longitudinal traction of moderate amount, but the amount of increase is less than can be accounted for by mere change of dimensions, so that the *specific* resistance of magnesium, like that of aluminium, is diminished by the temporary stress.

9. *When the permanent load on the wire is very small*, the temporary increase of length, like that of the increase of resistance, increases in larger proportion than the temporary load, but the former increases less rapidly than the latter, so that when the temporary stress exceeds a certain limit the above-mentioned decrease of specific resistance is changed to an increase of specific resistance.

10. The values of "Young's modulus," and the simple rigidity of the alloy, platinum-iridium, are much greater than those calculated from the same values for the components of the alloy.

11. The electrical resistance of platinum-iridium, quite unlike that of platinum-silver, German-silver, and brass, is much more increased by temporary longitudinal traction than that of either of the components of the alloy.

12. The increase of resistance mentioned above is much greater than can be accounted for by change of dimensions, so that the increase of *specific* resistance produced by longitudinal traction is considerably greater than is the case with any of those other metals examined whose resistance is increased by longitudinal traction.

13. The alteration of the resistance alluded to in 11 at first increases in greater proportion than the load, but when a certain limit of stress has been reached, the ratio of the temporary increase of resistance to the load producing it, begins to diminish, and finally reaches the same value as at first. A tendency to a similar state of things is seen with other metals, but in none is the phenomenon so pronounced as in platinum-iridium.

14. Unstretched platinum-iridium is thermo-electrically positive to the temporarily stretched metal.

15. The present investigations, as far as magnesium is concerned, confirm the previous ones in showing an apparent relationship between the "Hall effect" and the alteration of the specific resistance produced by mechanical stress. With regard to cobalt this is not so, at any rate for the metal when not under the influence of magnetic stress.

FIG 1.